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ORIGINAL ARTICLE

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Production and properties of Japanese oriented strand board I: effect of strand length and orientation on strength properties of sugi oriented strand board

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Abstract Oriented strand boards (OSB) were made using sugi wood strand with different lengths at different free fall distance conditions. Strand alignment and mechanical properties of sugi OSB were evaluated. Results obtained can be summarized as follows. The alignment angle distribution was greatly affected by both free fall distance and strand length. It was found that the standard deviation of the angles can be a measure for predicting the distribution when employing the von Mises distribution function with concentration parameter. The Monte Carlo simulation showed an agreement between the theoretical considerations and the experimental results on the strand alignment. The mechanical properties as affected by both strand length and layer structure were determined. Bending properties could be equal in both directions at 25% face layer ratio. Young's modulus obtained by the in-plane vibration method showed almost linear relation to the face layer ratio. No significant differences or only a slight difference was observed for the internal bond strength, plate-shear modulus, and nail resistance properties. Further studies are necessary.

Key words Oriented strand board · Strand alignment · von Mises function · Layer structure · Mechanical properties

Introduction

Oriented strand board (OSB) has been produced as a structural panel material substituting softwood plywood in North America since the early 1980s.[1] The great success of OSB as a wood-based material has strongly affected the panel industry and the market share of the panel supply in Japan. There are no OSB mills in Japan, although a few attempts are being considered to construct a mill that would use sugi wood. Sugi (*Cryptomeria japonica* D. Don), a fast grown Japanese cedar and widely planted in Japan, is one of the potential raw materials for OSB production. How to utilize sugi is still a major political issue for the forestry and wood industry in Japan.

Although many research works on waferboard and OSB have been done in North America,[2,3] only a few papers have been published in this field in Japan. Kajita reported the effect of alignment angle[4] and layer structure[5] on the properties of oriented particleboard using sugi thinnings. Saito et al.[6] studied OSB using veneer strands. Canadido et al.[7,8] reported the orthogonal properties of laboratory-made OSB. Yoshida et al.[9] and Sasaki et al.[10] reported the properties of electrostatically oriented particleboards. Iwata[11] reported that OSB with very thin strands had high performance and could be used as a substitute for lauan plywood. Further studies on OSB are necessary by both researchers and manufacturers for planning and constructing OSB mills in Japan.

The objective of this research was to evaluate the basic mechanical properties of OSB made with sugi wood. The focus of the research was on the effects of strand length and layer structure. There are also various production variables to be investigated for the development of sugi OSB. Alignment angles of sugi strands were determined, and the simulation was made for predicting strand angle distribution.

Materials and methods

Preparation of strands

Small-diameter sugi logs, Japanese cedar (*Chryptomeria japonica* D. Don) with air-dried density around 0.36 g/cm^3, were cut into blocks with dimensions of 20 mm in crossgrain direction and 30, 50, and 70 mm in grain direction. A disk flaker was used to cut strands from these blocks to an

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average thickness of 0.6 mm. Strand width (20 mm) and lengths (30, 50, and 70 mm) were controlled precisely for the model test of OSB. Strands were dried to a moisture content of less than 2% before glue spreading.

Board manufacturing

Types of board tested

The following four types of board were fabricated in this experiment.

UD: unidirectionally oriented homogeneous board
OOO: cross-oriented three-layer board
ORO: oriented three-layer board with random core layer
RD: randomly oriented homogeneous board

The three-layer boards, OOO and ORO boards, can be classified as OSBs as defined by a Canadian standard.[12] The random board (RD) is a type of waferboard.

The layer construction of the face/core ratio of three-layer boards was based on the oven-dried weight ratio of the furnish. Four kinds of cross-oriented board (OOO board) with different face/core/face ratios were fabricated: 5:90:5, 15:70:15, 25:50:25, 35:30:35. All ORO boards were made with a face/core/face ratio of 25:50:25.

Orienter

Strand alignment of the three-layer and UD boards was performed by passing the strands through plates spaced at 20 mm parallel to each other. Free fall distance (FFD), which is the distance between the end of the plates and the top of the mat oriented, was kept at 20 ± 5 mm.

Board fabrication

A laboratory-made box-type blender with dimensions of 600 × 600 × 450 mm was used for glue spreading onto the strands rotating inside at 25 rpm. To ensure uniform glue distribution, the optimal conditions on the rotation ratio, the amount of furnish for one glue shot, and the rate of air spray were determined by pretests. Specifications for board manufacturing were as follows.

Board size: 370 × 370 × 12 mm
Target density: 0.65 g/cm^3 in air-dried condition
Resin: liquid phenol-formaldehyde resin
Resin content: 6% solid/solid basis
Pressing conditions
  Temperature 180°C
  Pressure 2.5 MPa
  Time 10 min
Wax: not applied
Surface: not sanded

Properties test

The fabricated boards were cut to sizes of 300 × 300 mm, and the plate shear modulus was determined after reconditioning according to the ASTM standard.[13] Bending tests and internal bond tests were conducted according to the JIS standard.[14] In-plane Young's modulus was determined by the edgewise vibration method using a fast Fourier transform analyzer. From the peak frequency of the tapping tone, the elastic constant was calculated as follows.[15]

$$E = 48\pi^2 L^4 \rho f^2/(h^2 m^4)$$

where L is the length (300 mm), ρ the density, and h the height (50 mm) of the specimen; f is the peak frequency, and m is the constant (4.730 for the first vibration mode). A specimen with dimensions of 50 × 100 mm was used to determine the lateral nail resistance (LNR) and the nail withdrawal (NW) strength. CN-50 type nails were used for both tests, and a guide hole of 2.0 mm diameter was drilled 25 mm from the edge for LNR measurement. Seven specimens were used for the bending tests and the nailing tests, and four and fourteen were used for the plate shear test and the internal bond test, respectively.

Alignment angle measurement

To clarify the effects of strand length and FFD on the alignment angle distribution, photocopies of the strands aligned under different conditions were obtained. Using a digitizer on the image of the strands, data for angles between orientation direction and strand length direction were recorded on a personal computer. About 1000 aligned angle data were obtained for each FFD condition of 20, 40, 60, 80, and 100 mm and for those randomly oriented; 500 measurements were obtained for both 30 mm length and 70 mm length strands.

Results and discussion

Strand alignment

Effects of FFD and strand length

Figure 1 shows the relation between the strand alignment angle and the frequency obtained at various FFDs using 50-mm strands. The mean alignment value for each condition was almost zero because the angle was measured between $-\pi/2$ and $\pi/2$. It was obvious that the distribution curve became broader with increasing FFD. The normal distribution function seemed to be applicable as a regression curve when the FFD was small (e.g., 20 and 40 mm), where no aligned strands were found at an angle close to $\pi/2$ or $-\pi/2$. However, strand angles were distributed from $-\pi/2$ and $\pi/2$ at the FFD condition of more than 60 mm. A truncated normal distribution or another function was necessary for representing the angle data. When FFD further increased, the distribution became more even or constant. As shown in Fig. 1, strands were evenly distributed in the random board.

The standard deviation (SD) of the sampled strand angle data was used as a measure for evaluating the distribution. Figure 2 shows the effects of FFD on the SD measured at

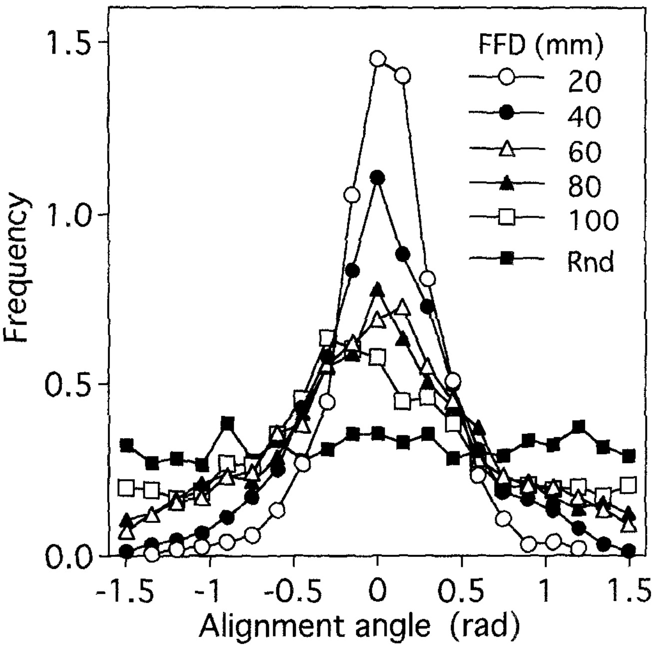

Fig. 1. Effect of the free fall distance (*FFD*) on the distribution of the strand alignment angle. *Rnd*, randomly oriented board

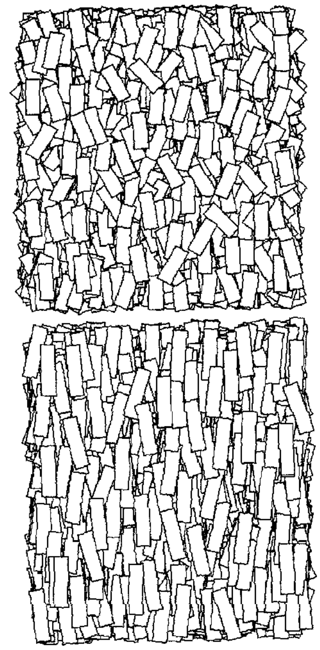

Fig. 3. Simulated mats with 50-mm strands (**top**) and 70-mm strands (**bottom**) aligned at 20 mm free fall distance

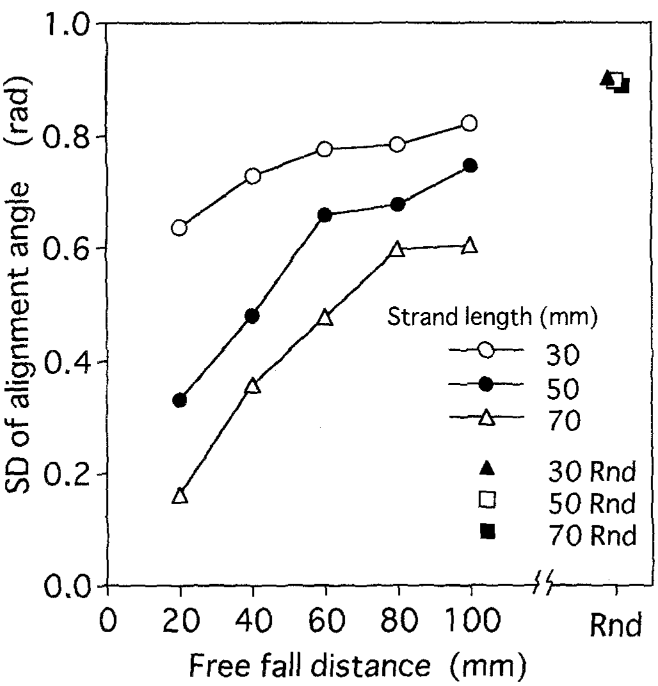

Fig. 2. Standard deviation (*SD*) of the angle measured for three strand length levels at various free fall distance conditions

various strand lengths. The smallest SD in this experiment, 0.162 radian, was observed at 70-mm strand length and 20 mm FFD condition. It was obvious that the SD increased with decreasing strand length and with increasing FFD. The SDs of the random boards were also plotted in Fig. 2. These values lay between 0.89 and 0.90 radian. The SD of the random board was supposed to be $\pi/12^{0.5}$ if the strand angle was evenly distributed from $-\pi/2$ to $+\pi/2$ with the constant probability of $1/\pi$. From the results shown in Fig. 2, the SD seemed to be a good indicator of the distribution of the strand angle of the board.

Strand angle distribution can be reproduced by a simulation if a cumulative frequency or a probability density function was defined using the experimental data as shown in Figs. 1 and 2. Figure 3 shows a simulated mat surface for both 50-mm and 70-mm strands formed with 20 mm FFD. These simulated mats can be used for a strength analysis of sugi OSB in future research.

Characterizing the distribution

Several methods have been introduced to evaluate the distribution of strand alignment. Geimer's "alignment percentage" is a measure used to determine the extent of alignment.[16,17] Lau[18] employed the normal distribution curve, and Harris and Johnson[19] used a truncated normal function and modified von Mises probability distribution function. Shaler[20] compared these measures. For characterizing the distribution of sugi strands, the modified von Mises function was employed in this study because of its flexibility in shape:

$$g(\theta, k) = 1/[\pi I_0(k)] \exp(k\cos 2\theta) \qquad (1)$$

where θ is the angle variable defined between $-\pi/2$ and $\pi/2$; k is the concentration parameter and; I_0 is the modified Bessel function of the first kind and order zero. This equation can well represent the strand alignment angle distributions obtained in Fig. 1. It becomes constant of $1/\pi$, when k is zero; and it changes shape gradually from a constant flat distribution to a sharp one like the normal distribution

Table 1. Results of curve fitting of strand angle distribution to the von Mises function

FFD[a] (mm)	Strand length (mm)	k^c	$I_0(k)^c$
20	50	3.51	7.46
40	50	1.82	2.02
60	50	1.12	1.34
80	50	0.911	1.22
100	50	0.661	1.11
∞[b]	50	0.032	1.00
20	30	1.04	1.29
20	70	11.3	9600

[a] Free fall distance
[b] Random board
[c] Refer to Eq. (1)

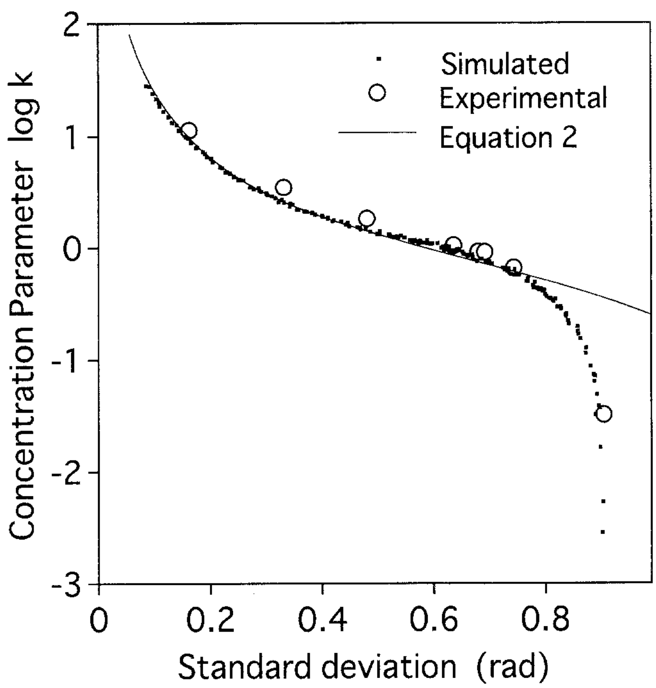

Fig. 4. Relation between standard deviation of the strand angles and the concentration parameter of the von Mises distribution function as evaluated by the Monte Carlo simulation and the experimental data

when k is increasing. Using the strand alignment data, a curve fitting Eq. (1) was made. The values k and $I_0(k)$ were determined by minimizing the summation of the square error and are shown in Table 1.

In this paper the SD shown in Fig. 2 was considered to be a measure of the distribution. DS and k in the von Mises function was related by the following equation.

$$SD = (\pi/2)^{0.5} I_0(k)\exp(k) \quad (2)$$

which could be derived from both Eq. (1) and the normal distribution function, substituting zero for θ in the equations. Using Eq. (2), we can determine the strand distribution represented by the von Mises function by obtaining the SD. Eq. (2) is shown in Fig. 4 as a solid line versus the experimental results. There was fairly good agreement between the theoretical equation and the experimental data, except the plot of the randomly aligned board.

Verifications

To verify the results obtained here, the relation between the SD and k was evaluated using a Monte Carlo simulation method.[21] In the simulation conducted here, about 200 mats were formed at different alignment conditions, and each mat had 2000 strands for the evaluation. The SD was for the simulated angle sample data, and k was obtained as follows: Using the data for 2000 samples, a histogram of the angle distribution was obtained for each mat, and k was determined by a curve fitting Eq. (1).

The simulated results were plotted in Fig. 4, which shows that the simulation results were in good agreement with the experimental results measured for the true sugi strand mats. This means that in the simulation the von Mises function can reproduce a strand distribution resembling the actual distribution during mat-forming, which had a wide range of alignment conditions from randomly oriented to highly oriented boards. The simulated results also agreed well with the line drawn by Eq. (2), where the SD was less than 0.8. The SD was known not to exceed the value $\pi/12^{0.5}$ (0.906), which was for the random boards, and the value of 0.8 was for the board with very poor orientation. Thus, Eq. (2) can be applied to all kinds of commercial oriented boards. Employing Eq. (2), we can estimate the distribution of the strand alignment by using only its standard deviation. This point could be useful for future research, which will proceed with a simulation of mat-formation analysis or provide a model for the strength properties of sugi OSB.

Mechanical performance

Bending properties

Figure 5 shows the effects of layer structure and strand orientation on the modulus of rupture (MOR) of sugi OSB. Comparing the mean values of random boards, the MOR of 70-mm strand boards was higher than that of 30-mm boards. This shows that longer strands can give a higher MOR because of effective contributions of the longitudinal properties of the wood itself to the board properties. As is well known, the orientation of strands causes an anisotropy in the mechanical properties of the oriented board. The MOR of UD board increased with increasing strand length in the parallel direction, whereas it decreased in the perpendicular direction. In addition to rather higher quality of longer strands, orientation of strands was greatly improved, as shown in Fig. 2. These were the reasons for the high bending properties in UD board with 70-mm strands. The mean values were around 70MPa for MOR and 10GPa for the modulus of elasticity (MOE) in the parallel direction and were comparable to the solid wood strengths. Strength greater than that of solid wood might be obtained with this type of product by improving the orientation and by elevating the compaction ratio more than twofold because sugi is a relatively low density species.

The MOEs obtained for the same conditions with MORs in Fig. 5 are listed in Table 2. The bending properties (MOR

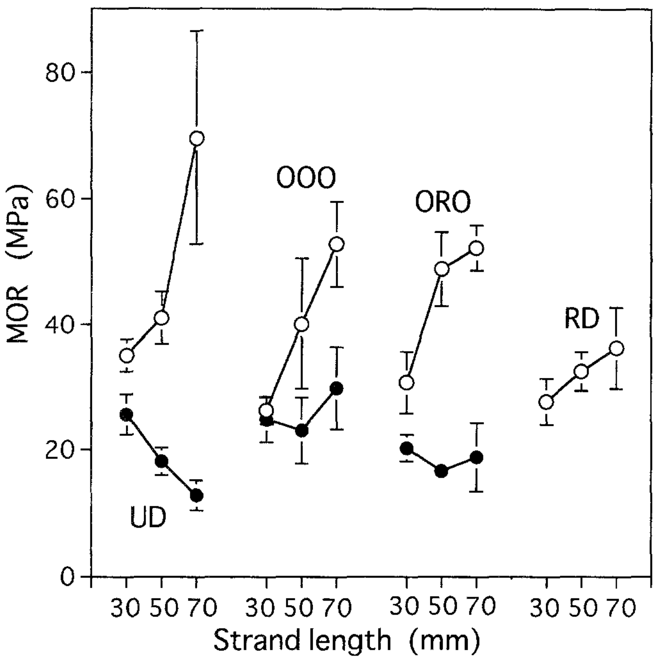

Fig. 5. Effects of strand length and layer structure on the modulus of rupture (*MOR*) of sugi OSB. *UD*, unidirectional homogeneous; *OOO*, cross-oriented three-layer; *ORO*, three-layer with random core; *RD*, randomly oriented homogeneous; *open circles*, parallel to the orientation; *filled circles*, perpendicular to the orientation

and MOE) in parallel direction of the three-layer boards (OOO and ORO) also increased with increasing strand length. There was no significant difference in the bending properties between the OOO board and the ORO board, which could be due to the fact that the surface layer property dominated the bending properties of the board. On the other hand, the strength in the perpendicular direction of the OOO board was slightly higher than that of the ORO board, which may be attributed to the high strength of the aligned core layer of the cross-oriented board.

Mechanical properties

Some mechanical properties are also listed in Table 2. Internal bond strength (IB) of the boards ranged from 0.40 to 0.58 MPa, and no significant difference was found between the board types tested. The IB values should be discussed in reference to the resin content, because it strongly depends on the amount of resin applied. Park et al.[22] used the same type of strands and reported that sugi strand board bonded with 10% PF resin satisfied the JIS requirement,[14] 0.3 MPa, but the board with 3% RC did not meet it. The results of the IB test here showed that a resin concentration of 6% was enough to obtain internal bonding in the sugi strand boards.

The plate shear modulus (Gp) is a modulus of rigidity related to the performance of boards when used as wall sheathing. OSB is generally known to have a higher shear modulus than plywood. The results showed that sugi strand boards also had a good Gp performance at around 1.5 MPa or more.

Table 2. Mechanical properties of sugi OSB at three strand lengths (30, 50, 70 mm)

Parameter	UD			OOO			ORO			RD		
	30	50	70	30	50	70	30	50	70	30	50	70
Density (g/cm^3)	0.67	0.70	0.71	0.69	0.70	0.72	0.68	0.68	0.70	0.66	0.68	0.69
	0.03	0.03	0.01	0.03	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01
MOR (MPa)												
Para	35.0	41.1	69.7	26.3	40.1	52.8	30.8	48.9	52.2	27.7	32.6	36.3
	2.6	4.2	17.0	2.2	10.4	6.8	4.9	5.9	3.6	3.7	3.1	6.5
Perp	25.6	18.1	12.8	24.8	23.0	29.9	20.3	16.6	18.9			
	3.2	2.2	2.4	3.6	5.3	6.6	2.1	1.7	5.4			
MOE (GPa)												
Para	5.07	6.53	10.6	4.31	6.33	8.01	4.77	7.12	8.56	3.77	4.00	4.56
	0.46	0.72	1.60	0.43	0.76	0.79	0.44	0.62	0.68	0.36	0.24	0.59
Perp	2.91	1.87	1.26	3.09	2.38	3.09	2.45	1.91	1.96			
	0.28	0.22	0.16	0.29	0.48	0.57	0.14	0.19	0.33			
IB (MPa)	0.55	0.47	0.48	0.54	0.46	0.50	0.49	0.51	0.46	0.58	0.53	0.40
	0.09	0.12	0.08	0.08	0.15	0.11	0.10	0.08	0.09	0.06	0.07	0.11
Gp (GPa)	1.66	1.48	1.54	1.51	1.52	1.64	1.48	1.48	1.51	1.58	1.67	1.77
	0.12	0.06	0.07	0.07	0.05	0.03	0.09	0.05	0.07	0.08	0.05	0.05
LNR (kN)												
Para	1.94	2.10	1.19	2.31	1.63	1.73	2.13	2.11	2.07	2.02	2.08	2.32
	0.54	0.24	0.36	0.12	0.62	0.37	0.17	0.25	0.38	0.36	0.28	0.16
Perp	2.03	2.13	1.75	1.90	2.05	1.78	2.32	1.90	2.10			
	0.38	0.36	0.17	0.38	0.38	0.32	0.07	0.21	0.14			
NW (kN)	0.25	0.34	0.43	0.25	0.36	0.45	0.32	0.32	0.40	0.28	0.42	0.46
	0.07	0.11	0.14	0.09	0.08	0.09	0.07	0.05	0.07	0.03	0.14	0.07

MOR, modulus of rupture; MOE, modulus of elasticity; IB, internal bond strength; Gp, shear modulus; LNR, lateral nail resistance; NW, nail withdrawal; Para, parallel to the orientation; Perp, perpendicular to the orientation; UD, unidirectionally oriented homogeneous board; OOO, cross oriented three-layer board with face core ratio of 25:50:25; ORO, oriented three-layer board with random core layer; RD, randomly oriented homogeneous board; OSB, oriented strand board

The mechanical properties of OSB related to nailing are important when it is used as a structural material. The results showed that the LNR values ranged from 1.6 to 2.3 kN for all the board types except for the 70-mm UD boards in the parallel direction. Because the variation of the data for the nail properties was large, no clear conclusion on the effects of the layer structure and strand length could be drawn here. However, NW values in Table 2 seemed to increase with increasing strand length, a subject to be addressed in future research.

Effects of layer construction

Figure 6 shows the relation between the face layer ratio and MOE when bending the three-layer cross-oriented boards. The face layer ratio was a weight ratio of the face and back to the total weight of the furnish. It was obvious that MOE in a parallel direction increased with an increase in the ratio; and the MOE in the perpendicular direction decreased with the ratio, creating a curve that seemed symmetrical to that in the parallel direction. If a simple combination of two different elastic bodies was introduced, the MOE of the three-layer board can be predicted by a cubic equation of the ratio, and the curves should be symmetrical. As was expected for the actual boards, the results showed some deviations from an ideal elastic consideration. A density profile in the thickness direction could be one of the factors to be discussed. The results also showed that the sugi OSB can be designed to have the same MOE in both directions with a face layer ratio of around 25%.

As shown in Fig. 6, the MOE obtained by the bending test was strongly affected by the face layer ratio and the strand orientation. In contrast to this out-of-plane bending, an elastic constant obtained by the in-plane bending vibration method was thought to give an arithmetic mean value based on the face layer ratio. Figure 7 shows the relations between the elastic constant (E), the in-plane direction, and the face layer ratio. The E value obtained here was regarded theoretically as the same elastic modulus obtained by tension or compression test stressed to the plane direction of the board. With an increase of the ratio, E in parallel direction increased and E in perpendicular direction decreased almost linearly. The difference in the behavior of the elastic constants shown in Figs. 6 and 7 was marked. These results showed that the strength properties of the three-layer oriented board could be designed by changing the face layer ratio.

Conclusions

Strand alignment angle distribution strongly depends on the free fall distance (FFD) and the length of the strands formed. It was found that the distribution can be characterized by the standard deviation and the concentration parameter of the von Mises distribution function. The Monte Carlo simulation revealed good agreement between the theoretical considerations and the experimental results on the strand alignment.

Bending properties were markedly affected by both the strand length and the layer structure of the sugi strand board tested in this experiment. Bending properties could be equal in both parallel and perpendicular directions at a

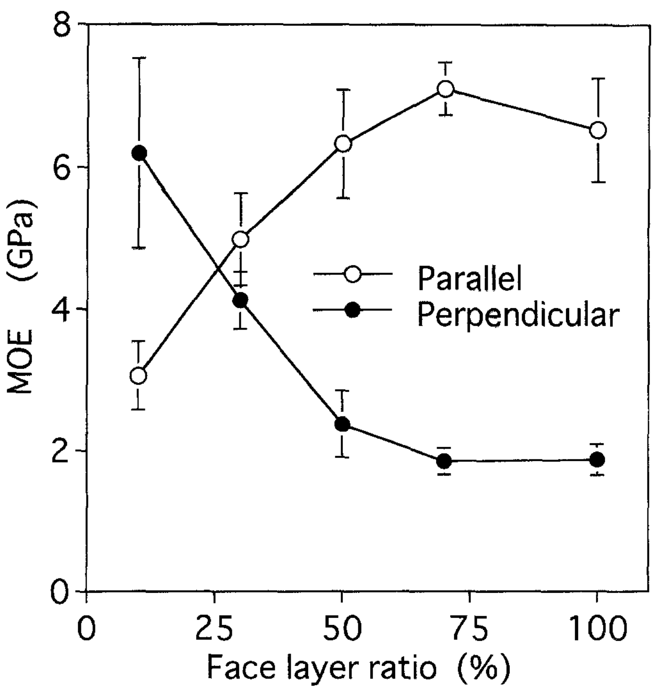

Fig. 6. Effect of the face layer ratio on the modulus of elasticity (MOE) of the cross-oriented three-layer sugi OSB

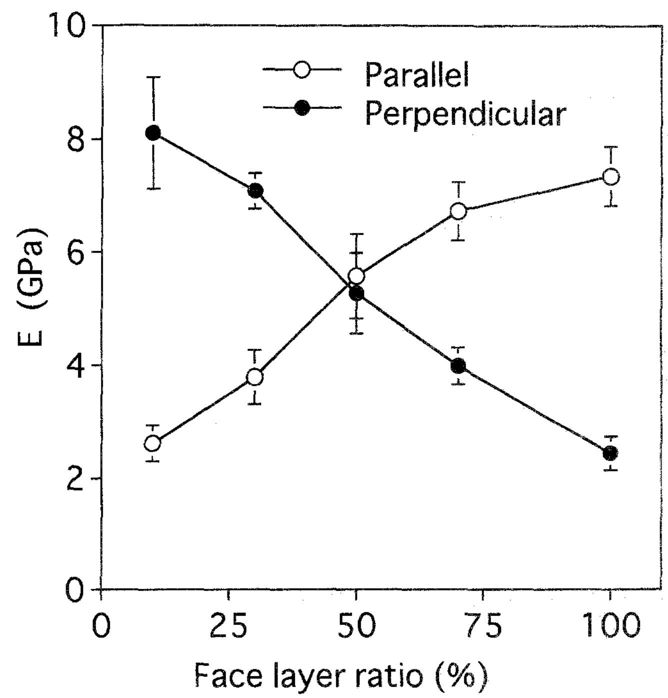

Fig. 7. Effect of the face layer ratio of the elastic constant obtained by the in-plane bending vibration method

25% face layer ratio. In-plane Young's modulus obtained by the vibration method showed almost linear dependence on the face layer ratio.

No significant, or only a slight, difference was found for the internal bond strength, plate-shear modulus, and nail resistance properties. Further studies are necessary to examine these properties.

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